Fan Cooler (FCL) Package
Reference Manual

The MELCOR ESF Package models the physics for the various Engineered Safety Features (ESFs) in a nuclear power plant. The Fan Cooler (FCL) package constitutes a subpackage within the ESF Package, and calculates the heat and mass transfer resulting from operation of the fan coolers. The removal of fission product vapors and aerosols by fan coolers is to be modeled within the RN package. Those models have not yet been implemented. This Reference Manual gives a description of the physical models and numerical solution schemes implemented in the FCL package.

User input for running MELGEN and MELCOR with the FCL package activated is described separately in the Fan Cooler Package Users' Guide.

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1. Introduction

The MELCOR ESF package models the thermal-hydraulic behavior of various engineered safety features (ESFs) in nuclear power plants. One important ESF is a fan cooler, which is a large heat exchanger used to remove heat from the containment building. Such coolers circulate hot containment atmosphere gases over cooling coils through which secondary water coolant at low temperatures is circulated. This results in the removal of heat by convection and condensation heat transfer.

The Fan Cooler (FCL) package constitutes a subpackage within the ESF package and calculates the heat and mass transfer resulting from operation of the fan coolers. The MELCOR model is based on the fan cooler model in the MARCH 2.0 code [1]. An effective heat transfer area is calculated in MELGEN from the rated primary and secondary flows and temperatures, and from the heat transfer coefficient and cooler capacity at those conditions. The actual heat transfer rate during a transient is then calculated using that effective area by evaluating the heat transfer coefficient from the current water vapor mole fraction, and by determining the average temperatures of the primary gas and secondary coolant, which are themselves implicit functions of the heat transfer rate, for conditions during the transient. A detailed model description is presented in the next section.

Several extensions to the MARCH model have been made. The user may optionally specify a separate discharge control volume for the fan cooler outlet air flow. The user may also specify a control function to switch the cooler on or off. The maximum condensation rate is limited to the water vapor inlet flow rate. Finally, the MELCOR implementation roughly partitions the total heat transfer coefficient into separate convection and condensation components to try to account for the effects of noncondensible gases and superheated atmosphere. The user can control how this partitioning is made by adjusting the sensitivity coefficients used in the heat transfer correlation.

The removal of fission product vapors and aerosols by fan coolers is not modeled within the FCL package. Models to simulate those processes have not yet been implemented, but will eventually be included in the RadioNuclide (RN) package.

2. Model Description

The total effective heat transfer coefficient, h_T, used in the MARCH fan cooler model is an empirical relation taken from the Oconee Power Reactor Final Safety Analysis Report [2] (British units of Btu/hr-ft^2-F have been converted to SI units of W/m^2-K):

$$h_T = 590.54 + 3603.4 X_{H2O} \qquad \text{for } X_{H2O} \le 0.26 \qquad (2.1)$$

$$h_T = h_T(0.26) + 2325.25(X_{H2O} - 0.26) \qquad for\ X_{H2O} > 0.26 \qquad (2.2)$$

where X_{H2O} is the water vapor mole fraction and h_T (0.26) in Equation (2.2) is evaluated from Equation (2.1) for X_{H2O} equal to 0.26, yielding a value of 1527.42. The heat transfer coefficient, h_T, is to be applied with the total effective fan cooler surface area, A_{eff}, and the temperature difference between the primary and secondary average fluid temperatures, $T_{P,\mathrm{avg}}$ and $T_{S,\mathrm{avg}}$, respectively. In MELCOR, it is assumed that this heat transfer coefficient can be divided into two components:

(1) a convective component, h_H, transferring only sensible heat, and

(2) a condensation component, h_M, transferring only latent heat.

The convective component is assumed to correspond to the heat transfer for completely dry conditions (i.e., X_{H2O}=0.0) times a sensitivity coefficient multiplier, F_H (default value of 1.0), such that

$$h_H = 590.54\, F_H \qquad (2.3)$$

It follows that

$$h_M = h_T - h_H \qquad (2.4)$$

The constants in Equations (2.1) through (2.3) have been implemented as sensitivity coefficient array C9001 (see Appendix A).

The total fan cooler heat transfer rate Q_T is therefore

$$Q_T = Q_H + Q_M \qquad (2.5)$$

where

$$Q_H = h_H A_{eff}(T_{P,avg} - T_{S,avg}) \qquad (2.6)$$

$$Q_M = h_M A_{eff}(T_{P,avg} - T_{S,avg}) \qquad (2.7)$$

The average primary and secondary fluid temperatures, $T_{P,avg}$ and $T_{S,avg}$, respectively, are themselves functions of the primary and secondary fluid inlet temperatures, $T_{P,in}$ and $T_{S,in}$, the primary and secondary mass flow rates through the fan cooler, W_P and W_S, and the fan cooler heat transfer rates. Assuming that the average primary temperature decreases only in response to sensible heat transfer, while the average secondary temperature increases in response to the total heat transfer results in:

$$T_{P,avg} = T_{P,in} - \frac{Q_H}{2 W_P c_{p,P}} \tag{2.8}$$

$$T_{S,avg} = T_{S,in} + \frac{Q_T}{2 W_S c_{p,S}} \tag{2.9}$$

where $c_{p,P}$ and $c_{p,S}$ are specific heat capacities at constant pressure for the primary and secondary fluids. Noting that $Q_H/Q_T = h_H/h_T$, simple substitution of Equations (2.8) and (2.9) into Equations (2.4) through (2.7) gives

$$Q_T = h_T A_{eff} \left[T_{P.in} - T_{S,in} - \frac{Q_T}{2} \left(\frac{1}{W_S c_{p,S}} + \frac{h_H / h_T}{W_P c_{p,P}} \right) \right] \tag{2.10}$$

Solving for the total heat transfer rate Q_T, Equation (2.10) gives

$$Q_T = h_T A_{eff} \frac{T_{P,in} - T_{S,in}}{\left[1 + \frac{1}{2} \left(\frac{h_T}{W_S c_{p,S}} + \frac{h_H}{W_P c_{p,P}} \right) A_{eff} \right]} \tag{2.11}$$

The maximum condensation heat transfer rate is also limited to the water vapor inlet flow rate:

$$Q_{M,\max} = Y_{H2O} W_P h_{fg} \tag{2.12}$$

where Y_{H2O} is the water vapor *mass* fraction and h_{fg} is the latent heat of vaporization of water. If Q_M is limited to $Q_{M,\max}$, Q_H and Q_T are recalculated from Equations (2.5) and (2.10).

The effective surface area A_{eff} is calculated in MELGEN from the rated primary and secondary flows and temperatures (W_{PR}, W_{SR}, T_{PR}, and T_{SR}), from the total and convective heat transfer coefficients evaluated at the rated water vapor mole fraction (h_{TR} and h_{HR}), and from the cooler capacity Q_R at those conditions, using Equation (2.10):

$$A_{eff} = \frac{Q_R}{h_{TR}(T_{PR} - T_{SR}) - \frac{Q_R}{2}\left(\frac{h_{TR}}{W_{SR}c_{p,S}} + \frac{h_{HR}}{W_{PR}c_{p,P}}\right)} \tag{2.13}$$

Here, W_{PR} is the rated primary mass flow, related to the rated volumetric flow input by

$$W_{PR} \equiv \rho_{PR}\, \dot{V}_{PR} \tag{2.14}$$

Where the gas density, ρ_{PR}, is evaluated at T_{PR} and a pressure of one atmosphere (101325 Pa).

Note that, unlike the MARCH model, conditions actually used in the transient calculation in MELCOR may, in general, be different from rated flows and temperatures.

All mass and energy transfers calculated by the fan cooler model are communicated to the Control Volume Hydrodynamics (CVH) package through the standard interface provided for such interpackage transfers.

Fan coolers may be specified for any control volume. The user may optionally specify a separate discharge control volume for the fan cooler outlet air flow, in which case the cooler functions somewhat like a flow path with a constant volumetric flow (that is cooled or dehumidified) from the inlet volume to the discharge volume. Operation of the cooler may be tied to other facets of the calculation by use of a control function to switch the cooler on or off.

3. Discussion and Development Plans

The MELCOR peer review [3] found that use of the Oconee FSAR correlation for the total heat transfer coefficient and the MELCOR approach to partitioning it into a condensation component dependent on water vapor mole fraction and a constant sensible convection component to be deficient because they do not adequately represent the underlying physics. However, this model was deemed relatively unimportant for most PRA applications, since fan coolers either are assumed operational, in which case they have far more capacity than is needed to remove decay heat or are assumed inoperative.

However, for recovery scenarios investigated as part of accident management analyses, errors in calculating condensation rates would impact assessments of the dangers of de-inerting the containment atmosphere and causing burns. Concern was also expressed that the modeling limitations could become important for relatively low-capacity units (e.g., room coolers and non-safety grade fan coolers used for normal heat loads).

Mechanistic models (e.g., from CONTAIN [4]) could be fairly easily adapted for use in MELCOR if found necessary for accident management applications, but there are no current plans to do this.

Appendix A: Sensitivity Coefficients

This section lists the sensitivity coefficients in the FCL package associated with various correlations and modeling parameters described in this reference manual.

Coefficient	Default Value	Units	Equation
C9001(1)	590.54	W/m^2-K	2.1, 2.3
C9001(2)	1.0	-	2.3
C9001(3)	0.26	-	2.1, 2.2
C9001(4)	3603.4	W/m^2-K	2.1
C9001(5)	2325.25	W/m^2-K	2.2

References

1 R.O. Wooton, P. Cybulskis, and S.F. Quayle, MARCH 2 (Meltdown Accident Response Characteristics) Code Description and User's Manual, NUREG/CR-3988, BMI-2115 (August 1984).

2 Duke Power Company, Oconee Nuclear Station Units 1, 2, and 3: Final Safety Analysis Report (1987).

3 B. E. Boyack, et al., MELCOR Peer Review, LA-12240, Los Alamos National Laboratory (March 1992).

4 K. K. Murata, et al., Code Manual for CONTAIN 2.0: A Computer Code for Nuclear Reactor Containment Analysis, NUREG/CR-6533, SAND97-1735, Sandia National Laboratories (December 1997).